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ENGINEERING PROPERTIES OF SUBSEA PERMAFROST IN THE PRUDHOE BAY --ETC(U)
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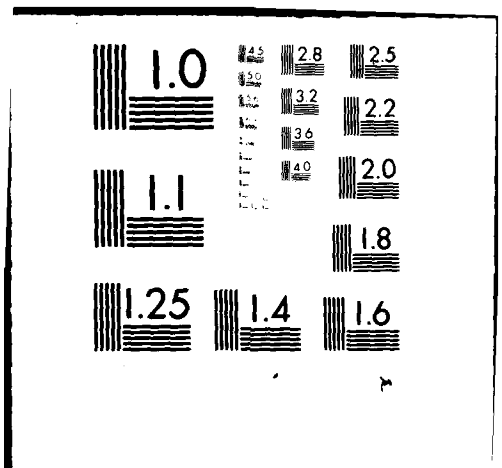

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6) # ENGINEERING PROPERTIES OF SUBSEA PERMAFROST IN THE PRUDHOE BAY REGION OF THE BEAUFORT SEA

N00014-75-C-0635

10) Edwin J. Chamberlain[1], Paul V. Sellmann[1], Scott E. Blouin[1], David M. Hopkins[2] and Robert I. Lewellen[3] 1977

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INTRODUCTION

Recent investigations (Hunter et al. 1976, Osterkamp and Harrison 1976, Lewellen 1976) support earlier indications that permafrost is very extensive under the Beaufort Sea.

During the spring of 1976, a drilling program was conducted along a transect from 1 to 17 km offshore of Prudhoe Bay, Alaska, to obtain data on the vertical and horizontal distribution and the engineering and chemical properties of subsea permafrost (Sellmann et al. 1976). This extended the line previously investigated by Osterkamp and Harrison (1976). Core samples were obtained for laboratory determinations of index, strength, and compressibility properties as well as for sediment chemistry. In addition, in-situ measurements of penetration resistance and temperature were obtained. Supporting geological, thermal, dating, and fossil studies were undertaken by the U.S. Geological Survey to aid in interpreting the geologic history of this region.

SITE LOCATIONS

Three holes were drilled offshore in the Prudhoe Bay area using the sea ice cover as a drilling platform. One of the sites was within Prudhoe Bay and the others were north and south of Reindeer Island (Fig. 1). Water depths and distances from shore are given in Figures 2-5.

The sites were selected to include a range of thermal and geological settings controlled by distance from shore, occurrence of offshore islands and bars, and water depths. The University of Alaska drilling program conducted in 1975 near and offshore of the new ARCO dock facility (Osterkamp and Harrison 1976) and geophysical studies in the Prudhoe Bay area (Rogers 1976) were helpful in determining site locations. The study by Osterkamp and Harrison (1976) established the existence of bonded permafrost in two holes in areas of shallow water <2 m in depth. Their deepest offshore hole (46 m), located approximately 3370 m from shore, did not penetrate into bonded permafrost.

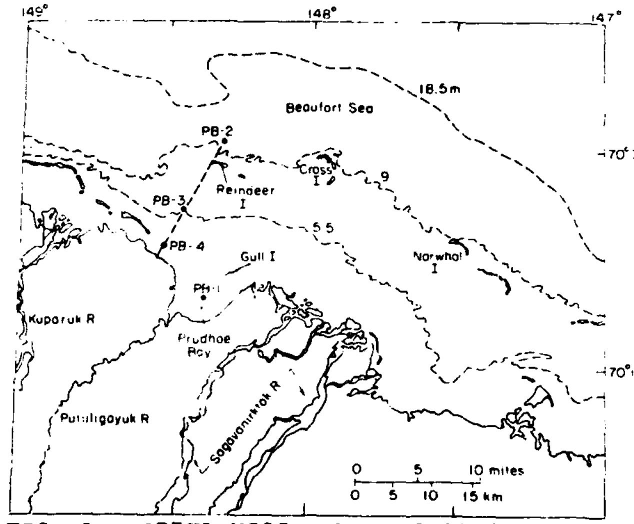

FIG. 1. CRREL-USGS subsea drilling location, Prudhoe Bay region, spring 1976.

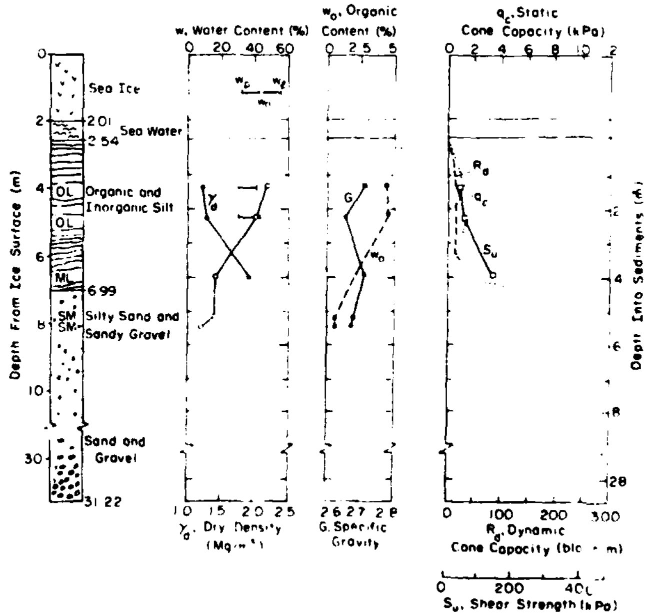

FIG. 2. Engineering properties and hole logs for site PB-1, approximately 2.8 km from shore.

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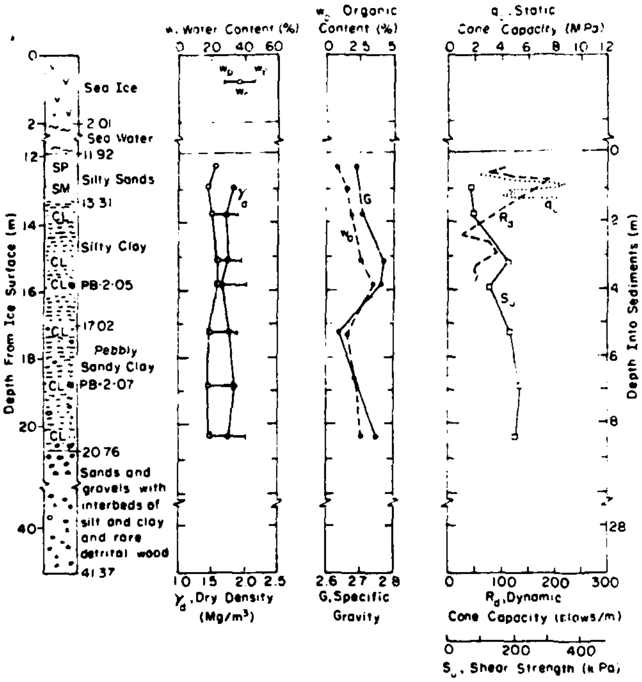

FIG. 3. Engineering properties and hole logs for site PB-2, approximately 17 km from shore.

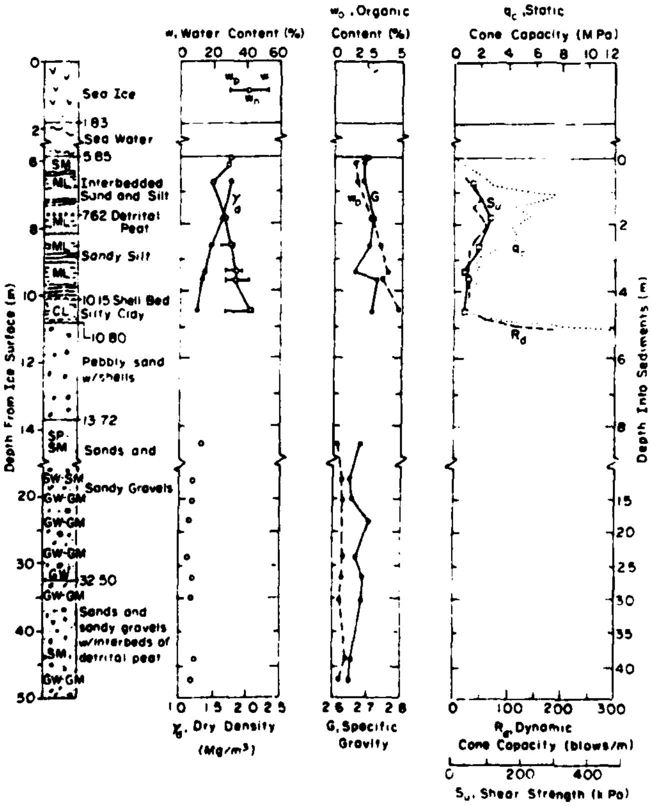

FIG. 4. Engineering properties and hole logs for site PB-3, approximately 6.5 km from shore.

HOLE LITHOLOGY AND SAMPLE PROPERTIES

The drilling and sampling techniques used during the project have been described in detail by Sellmann et al. (1976).

The hole logs shown in Figures 2-4 are based on field observations of cores, wash samples and drilling conditions, and results of laboratory analysis. The logs all show a fine-grained surface section of marine sediments (fine sand, silt and clay) 4.5 to 6.8 m thick. These sediments commonly contain a few rounded pebbles, perhaps material ice-rafted from nearby beaches. These appear to overlie beach sediments (well-rounded gravel, coarse sand and some mud). The lower part of the marine mud sequence at site PB-2 contains abundant small pebbles and granules. The fine-grained marine materials are soft and weak at sites PB-1 and PB-3 while at site PB-2 they appear to be very stiff and overconsolidated.

The marine sequence is underlain by poorly sorted angular gravel lacking any organic remains, probably deposited as glacial outwash. The outwash appears to be approximately 18 m thick at sites PB-1 and PB-3 and less than 5 m thick at PB-2. All boreholes terminate in an alluvial section of well-sorted sand, pebbly sand and gravel containing lenses of detrital wood and plant fragments.

The index properties and Unified Soil Classifications are given in Figures 2-4. It can be seen, with few exceptions, that the fine-grained silts and clays at sites PB-1 and PB-3 have the high moisture contents commonly encountered in marine environments, while the clays at site PB-2 have lower water contents in the range of their plastic limits.

EXPERIMENTAL PROGRAM

Cone Penetrometer Field Tests

Both dynamic and static penetrometer tests in the sediments were conducted using the sea ice as a platform. For the dynamic tests, a standard 64-kg hammer dropped 0.76 m was used to drive the probe string, which was made up of EW drill rod surrounded by EX casing. The probe consisted of a 60° hardened steel cone attached to the drill rod and a 150-mm-long sleeve welded to the base of the casing. The cone and sleeve both had a diameter of 57 mm. The point and sleeve could be driven simultaneously or separately by temporarily adding 0.3-m sections of casing or rod at the top of the probe string as desired. The static penetrometer used the same probe string and was pushed by a hydraulic cylinder mounted atop a quadrapod anchored to the sea ice.

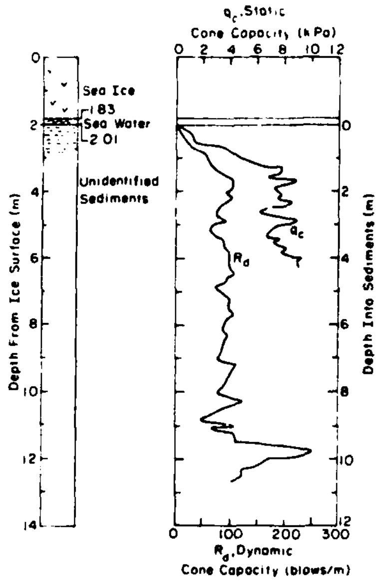

FIG. 5. Static and dynamic cone capacities for site PB-4, approximately 0.8 km from shore.

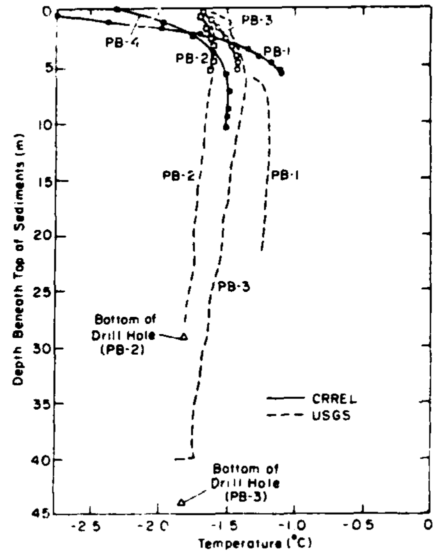

FIG. 6. Temperature profiles for Prudhoe Bay sites 01, 02, 03 and 04 (USGS data from Marshall, personal communication).

The results of the tests are illustrated in Figures 2-5. At site PB-1, the static penetration resistances were very low (<2 MPa) throughout the fine-grained section. Upon entering the coarser-grained sands and gravels the static penetration resistance rapidly increased to 24 MPa. Because of equipment difficulties, dynamic penetration data were obtained only in the fine-grained section. The range of penetration resistances was between 12 and 24 blows/m.

At site PB-2, a few static penetration results were obtained, but they are of questionable quality because of rod buckling problems in the deep water. The dynamic cone capacity rises sharply in the upper 1.4 m of silty sand to nearly 200 blows/m and falls abruptly to 50 to 100 blows/m in the clays beneath.

The cone penetration data at site PB-3 show the best correlation. Both the static and dynamic cone penetration data show an increase of penetration resistance through the upper meter of loose silty sand, a relatively constant penetration resistance through the next meter of more compact silt, and a decrease in the next 0.5 m of softer silts to a relatively low penetration resistance in the next 2-1/2 m of very soft silt. At a penetration depth of approximately 5 m a very stiff layer of sand was encountered and the penetration resistance increased rapidly with increasing penetration depth.

At site PB-4, the greatest penetration depth (11 m) was achieved, using the dynamic cone penetrometer. The penetration resistance increased from 100 blows/m below a depth of 2 m to nearly 250 blows/m near 10 m of penetration. The static cone penetration resistance increased to 8 MPa at the 2-m penetration depth and remained constant to 5-m depth.

In Situ Temperature Profiles

Equilibrium temperature data were obtained through the bore of the cone penetration rod at four sites. With the exception of site PB-1 where convection problems occurred, the resulting temperature profiles compared well with the data obtained by the USGS (V. Marshall, pers. comm) in Figure 6.

The bottom temperatures at the shallow water sites PB-1 and PB-4 where the salt concentrations were high because of restricted flushing under the sea ice cover were -3.25°C and -2.30°C respectively while the bottom temperatures at the deeper water sites PB-2 and PB-3 were both approximately -1.70°C. Negative temperature gradients occur at all sites below sediment depths of 5 to 12 m. This suggests that ice-bonded permafrost is present in the sediments below.

Laboratory Strength Tests

Undrained-unconsolidated triaxial compression tests were conducted at confining pressures estimated to be equivalent to the in situ overburden pressures on samples prepared from core specimens obtained from the three drill sites. The samples were 50 mm in diameter and 115 mm in length. The tests were conducted at a constant rate of strain of approximately 0.045/min. at 0±1°C. The samples were not ice-bonded as chemical analysis of the pore water revealed that the freezing point was -1.8°C or lower.

For site PB-1, Figure 2 illustrates that to a depth of 5 m or more the sediments are weak, the maximum shear strength being 45 kPa, while at a depth near the boundary of the fine-grained marine sediments and the coarser-grained glacial outwash material the shear strength increases to 134 kPa.

At site PB-2 (Fig. 3), there is a gradual but significant increase of shear strength with depth. In the overlying sandy material the shear strength is approximately 84 kPa. Near the top of the stiff marine clay section the strength is only a slightly greater 92 kPa but it increases to 225 kPa near the bottom.

At site PB-3 the shear strength decreases with depth (Fig. 4) in the marine section as softer and finer-grained materials are encountered. In the upper half of this section the strength is as high as 107 kPa while near the bottom it is approximately 28 kPa.

Laboratory Consolidation Tests

Because the clay samples taken from site PB-2 appeared to be overconsolidated, laboratory consolidation tests were conducted on two selected samples, one obtained from core PB-2-05 and the other from PB-2-07. These tests revealed overconsolidation stresses of 3800 and 3600 kPa respectively, the resulting overconsolidation ratios being 99 and 53.

DEPTH TO ICE-BONDED PERMAFROST

As no ice-bonded samples were recovered, it was initially concluded that ice-bonded permafrost lay at some unknown distance beneath the bottom of the drill holes. However, because of the extremely difficult driving conditions at the termination depths at PB-2 and PB-3, it was suspected that ice-bonded permafrost might have been encountered.

From the chemistry data of Iskandar et al. (1978) it was estimated that the freezing point of the interstitial water at both sites was approximately -1.8°C. Extrapolating the straight line segments of the USGS (1976) temperature profiles downward to intercept the -1.8°C isotherm resulted in estimated depths to ice-bonded permafrost for sites PB-2 and PB-3 of 29.9 and 43.3 m respectively (see Fig. 6). These depths correlate extremely well with the 29.5- and 44.2-m depths at which drilling and sampling were terminated because of collapsed casing or very high penetration resistances. It appears then that the depth to ice-bonded permafrost is less at the site most distant from shore.

OVERCONSOLIDATED CLAYS AT SITE PB-2

Distribution in the Beaufort Sea

The fact that highly overconsolidated clays were observed at only one of the three sites drilled leads to the conclusion that they may occur only in special marine environments. Reimnitz et al. (1974) reported finding stiff silty clays approximately 1 km seaward off Egg Island near Simpson Lagoon. In addition, Hollingshead and Rundquist (1977) reported that overconsolidated clays have been observed in shallow waters of the Mackenzie Delta.

Possible Mechanisms

Many overconsolidation mechanisms exist but only the traditional factors of 1) overburden pressure and subsequent erosion, 2) desiccation, and 3) glaciation, and the lesser-known mechanisms such as 4) freezing and thawing and 5) the forces of drifting berg ice or sea ice were considered.

To evaluate these mechanisms the geologic and climatic history of the nearshore Beaufort Sea must be known.

Geologic and Climatic History

Osterkamp and Harrison (1976) dated the sands and gravels underlying the marine clays at approximately 22,000 years BP. Barnes and Reimnitz (1974) stated that these clays are pre-Holocene or more than 7,000 to 10,000 years old, but stratigraphic, paleontologic and geochronologic study of our samples show that they are, in fact, Holocene, and range in age from contemporary to perhaps 10,000 years old. This period of time was characterized by a retreat of continental glaciation and a rise in sea level. Short term glacial advances may have occurred. However, reported glacial-geological studies indicate that none of these advances could have extended out onto today's coastal plain (Hamilton and Porter 1975). Sea level fluctuations occurred in this region throughout the late Pleistocene time in response to varying amounts of water being tied up on the continent in the form of glacier ice. Within the last 20,000 to 30,000 years the sea level was 100 m lower than at present, and has been rising continuously since, although at a varying pace during the period in which the marine clays accumulated (Hopkins 1973, Hopkins et al. 1977).

Evaluation of Overconsolidation Mechanisms

Glacial loading can be readily eliminated as an overconsolidation mechanism since there is no evidence that this part of the coastal plain has been glaciated since the time the marine clays were deposited.

Sediment loading and erosion can be excluded as an independent mechanism since adequate overburden thicknesses have not been available. It appears that since the deposition of the marine clays, no land surface at site PB-2 could have been more than a few meters above the existing sea level. The laboratory tests indicate that an overburden thickness of approximately 350 m of submerged sediment or 175 m of elevated sediment is necessary to overconsolidate these marine clays to their present state.

It has been suggested that the forces of drifting ice or pressure ridges may be factors in the overconsolidation process. However, there is little evidence that ice forces would compact the sea floor sediments. On the contrary, Reimnitz and Barnes (1974) have observed that rather than compressing the sea floor sediments, the ice would dislodge them and cast them aside. The process would be one of bulking, particularly in the soft marine sediments where there is little or no strength.

Desiccation is a common mechanism for overconsolidating clay soils. However, the necessary exposure of these marine sediments to the atmosphere would also mean that they would be subject to low temperatures and frozen.

Because temperature conditions appear to have been favorable over much of the late Pleistocene time for deep freezing of exposed land surfaces, and because more conventional overconsolidation processes do not appear to be viable, the process of freeze-thaw consolidation was given serious consideration. A discussion of this process is given by Chamberlain and Blouin (1978).

Freeze-Thaw Consolidation Tests

The results of two freeze-thaw consolidation tests conducted at an applied effective stress level of 128 kPa are superimposed on the undisturbed loading curve in Figure 7. The PB-2-05 and PB-2-07 materials were reconstituted in the form of slurries, deaired, and fully consolidated under successively increasing pressures to 128 kPa (approximately the pressure of 13 m of submerged sand or the thickness of Reindeer Island) and then frozen unidirectionally and allowed to thaw. For sample PB-2-05 (Fig. 7), the void ratio decreased 24% from 0.973 to 0.748. Similar results were obtained for sample PB-2-07.

Because of the uncertainty of the influence of freezing rate and the effects of drying and wetting on these materials when reconstituted for testing purposes, the differences noted in Fig. 7 between the thawed and undisturbed void ratios are not considered significant. Thus, these tests demonstrate that freezing and thawing is a viable mechanism for overconsolidating the marine clay sediments at site PB-2.

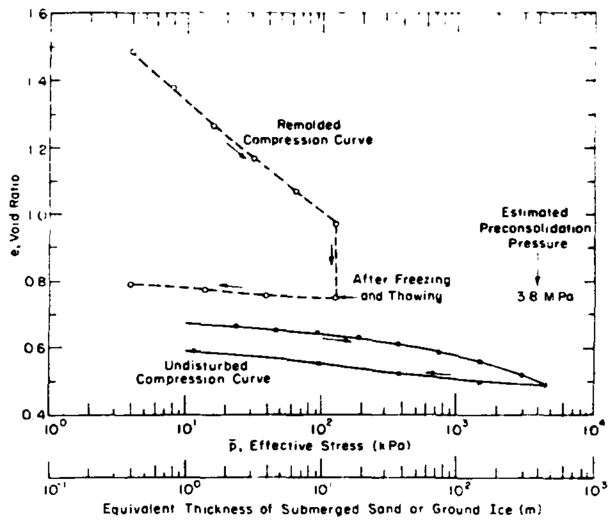

FIG. 7. Compression curves for undisturbed and remolded-thawed material from site PB-2-05.

This explanation is, of course, dependent upon these sediments being frozen during a period of rising sea level. Thus, some process providing for heat transfer between the cold arctic air and the marine clays must have occurred.

Processes for Inducing Freezing

There appear to be three distinctly different processes for providing a good thermal connection or "thermal bridge" between the marine sediments and the cold arctic air. The transgression of a barrier island, such as nearby Reindeer Island, across site PB-2 would provide the "thermal bridge" required. Since it is known that Reindeer Island is migrating westward and shoreward from site PB-2 (Hopkins et al. 1977) and that the depth of ice-bonded sediments at Humble Oil Company's hole C-1 on Reindeer Island is almost precisely the required frost penetration depth (20 m), this appears to be the most likely process.

However, it is also possible that perturbations in the sea level curve or grounding of berg ice or massive sea ice structures could have provided the necessary "thermal bridge." Since little is known of short-term lowering of the sea level in the past 10 thousand years and because grounded ice would result in only limited bed contact and freezing depths, these latter two processes appear to be less likely.

CONCLUSIONS

1. Subsea sediment temperatures were below 0°C at all sites studied during the spring of 1976.

2. Ice-bonded permafrost did not occur within the upper 30 m of subsea sediments in a region extending from 1 to 17 km offshore.

3. Negative gradients in thermal data and analysis of pore water chemistry suggest that ice is present at 29.9- and 43.3-m depths at sites PB-2 and PB-3 respectively. Because site PB-2 is in the deepest water and is at the greatest distance from shore, it appears that the depth to ice-bonded permafrost decreases with increasing distance from shore at these sites.

4. Shallow, highly overconsolidated marine clays occur seaward of Reindeer Island, while softer marine muds occur inside the barrier island along our study line.

5. The dense marine clays probably have been overconsolidated by freezing and thawing. The most likely process appears to involve freezing of the marine sediments during transgression of a barrier island across the site.

6. In-situ cone penetration resistance data can be obtained using the sea ice as a platform. This information can be used to delineate the occurrence of soft and stiff marine materials as well as dense sands and gravels and provide rapid access to thermal data.

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REFERENCES

BARNES, P.W. and E. Reimnitz. 1974. Observations of arctic shelf processes from marine geologic studies conducted off the northern coast of Alaska. Preliminary report distributed at the Beaufort Sea Coastal Symposium, 7-9 January 1974.

CHAMBERLAIN, E.J. and S.E. Blouin. 1978. Densification by freezing and thawing of fine material dredged from waterways. This volume.

HAMILTON, T.D. and S.C. Porter. 1975. Itkillik glaciation in the Brooks Range, Northern Alaska. Quat. Res. 5, pp. 471-497.

HOLLINGSHEAD, G.W. and L.A. Rundquist. Morphology of Mackenzie Delta channels. Undated report received 31 January 1977.

HOPKINS, D.M. 1973. Sea level history in Beringia during the past 250,000 years. Quat. Res. 3, pp. 520-540.

HOPKINS, D.M. P.W. Barnes, N. Biswas, J. Cannon, E. Chamberlain, J. Dygas, W. Harrison, A.S. Naidu, D. Nummedal, J. Rogers, P.V. Sellmann, M. Vigdorchik, W. Wiseman and T. Osterkamp. 1977. Earth science studies. In Synthesis of environmental studies of the continental shelf of the Beaufort Sea. National Oceanic and Atmospheric Adminstration, in press.

HUNTER, J.A.M., A.S. Judge, H.A. MacAulay, R.L. Good, R.M. Gagne and R.A. Burns. 1976. Permafrost and frozen sub-sea-bottom materials in the Southern Beaufort Sea. Beaufort Sea Technical Report #22, Beaufort Sea Project, Canadian Department of the Environment.

ISKANDAR, I.K., T.E. Osterkamp and W.D. Harrison. 1978. Chemistry of interstitial water from subsea permafrost, Prudhoe Bay, Alaska. This volume.

LEWELLEN, R. 1976. Subsea permafrost research techniques. Symposium on Research Techniques in Coastal Environments, Louisiana State University, March 18-19, 1976.

OSTERKAMP, T.E. and W.D. Harrison. 1976. Subsea permafrost at Prudhoe Bay, Alaska - Drilling report. University of Alaska Scientific Report UAG R-245, Sea Grant Report No. 76-5.

REIMNITZ, E. and P.W. Barnes. 1974. Sea ice as a geologic agent on the Beaufort Sea shelf of Alaska. Preliminary report distributed at the Beaufort Sea Coastal Symposium, 7-9 January 1974.

REIMNITZ, E., C.A. Rodrick and S.C. Wolf. 1974. Strudel scour: A unique arctic marine geologic phenomenon. J. Sed. Pet. 44(2), pp. 409-420.

ROGERS, J.C. 1976. Seismic investigation of offshore permafrost near Prudhoe Bay, Alaska. Unpublished report.

SELLMANN, P.V., R.I. Lewellen, H.T. Ueda, E.J. Chamberlain and S.E. Blouin. 1976. 1976 USACRREL-USGS subsea permafrost program, Beaufort Sea, Alaska - Operational report. CRREL Special Report 76-12.